Digital Beamforming for Simultaneous Power and Information Transmission in Wireless Systems

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***Abstract*—This paper proposes a Beamforming algorithm for simultaneous transmission of information and power in multi-antenna linear array system. Here we considered three node system in which transmitter and receiver are largely separated from each other whereas energy harvesting circuit is co-located with the information receiver i.e. encounters the same channel from the transmitter. Our primary motto is to maximize the energy harvested by the harvester circuit, at the same time maintaining the information rate above a certain threshold level. Firstly, we used an algorithm to steer the antenna beam in a desired direction. Secondly, we combined this algorithm with another algorithm that maximizes the harvested energy. The hybrid algorithm produces an improvement in the result in terms of received signal level and side-lobe level. Finally, simulation results are presented to justify the effectiveness of the proposed algorithm.**

***Index terms*— Beamforming, Fading, Capacity, Information rate, Energy harvesting, Power optimization, MIMO, Sensor Networks.**

I. Introduction

Worldwide Energy constraints are regarded as one the most fundamental limitation in the field of wireless and mobile communication. As there are increase in the number of wireless and portable mobile devices, charging of these devices has become a critical problem. Portable devices contain small batteries that put a limitation on the service time. The batteries are either replaced or re-charged, both of which counts for user's attention and moreover the batteries have limited life time. One of the methods to increase the lifetime is to obtain the energy from the environment. A number of methods to harvest energy from the environment such as solar, RF, wind etc. are available. But we will here consider only RF energy harvesting. The signal from the transmitter along with interfering signals can be an important source for RF energy harvesting. Such harvesters can have a number of utilities such as-radio frequency identification system (RFID) systems, Medical sensors, Wireless sensor networks etc.

This paper investigates wireless networks in which the devises do not have power source, but run by the energy harvested from the received signal intended to itself or to other devices in the network. Here we consider a simple system model consisting of three nodes-a transmitter, a receiver that decode information and another receiver that harvest energy as shown in Fig. 1. The two receivers (Energy and Information) can be either separate or co-located. Here we consider the scenario in which the energy and information receivers are separated i.e. the signal from the transmitter to the energy and information receivers suffer from different channel path gains. We study transmission strategy to achieve maximum energy transfer, at the same time maintaining the information rate above a threshold level. The scenario in which the receivers are co-located can be solved similarly as the above, considering same channel path gains. However, the practical circuit limitations make this scenario of co-located receivers infeasible.

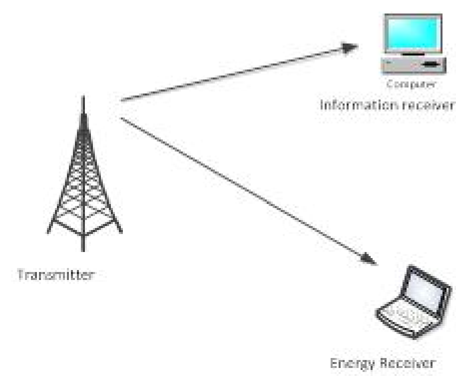

Figure 1. A three node wireless system for simultaneous power and information transmission

Several methods such as Inductive coupling, Electromagnetic (EM) radiation and Magnetic resonant coupling along with their strength and limitations have been stated in [1,2]. EM radiations require small receivers and power is transmitted for large distance, but there is rapid fall in transfer power efficiency over distance. A transmit beamforming scheme for MIMO wireless channel, which follows the idea of maximizing SLNR (signal-to-leakage-plus noise ratio) and needs no additional power allocation is stated in [3]. Simultaneous power and information transmission for noisy channel has been extensively studied in [4, 5]. Beamforming is an important signal processing technique that utilizes the channel state information (CSI) at the transmitter for information transmission and to increase the signal strength at the receiver [6-8].

The goal of this paper is to propose a beamforming algorithm that will steer the signal in the desired direction and at the same time the signal strength at the receiver is maximized keeping the information rate above a threshold level.

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Remaining paper is organized as follows. Section II presents system model and problem formulation. In section III, the proposed algorithm is discussed. Simulation results are presented in section IV. Finally, we conclude this paper.

Notation: $(\cdot)^H$ represents Hermitian transpose. |y| denotes absolute value of the scalar y. log (·) is taken to the base 2 and ||y|| denotes the Euclidean norm of the vector **y.**

II. System Model and Problem Formulation

As shown in Fig.1, we consider a three node communication system in which transmitter has L antennas and each receiver has single antenna.

A. Signal Steering

To transmit the signal to greater distance and to increase the probability of detection, complete signal is to be transmitted in only the desired direction. Signal, when transmitted in single direction, reduces the possibility of interference to users in other direction.

Consider a general bandpass signal s(t), used to transmit information is given as:

$$s(t, p_n) = \sqrt{2}\mathrm{Re}\{s(t, p_n)e^{j\omega_c t}\}, \quad n = 0, \ldots\ldots, L-1, \tag{1}$$

where w_c is the career frequency and $s(t, p_n)$ is complex envelop, Considering signal as plane wave (1) can be expressed as:

$$s(t, p_n) = \sqrt{2}\mathrm{Re}\{\tilde{s}(t - \tau_n)e^{j\omega_c(t-\tau_n)}\}, \quad n = 0, ., L-1, \tag{2}$$

Where τ_n is given by:

$$\tau_n = \frac{\bar{k}^T \overline{p_n}}{\omega_c} \tag{3}$$

A signal s(t, p) having complex envelop $\tilde{s}(t, p_n)$ and bandwidth B_s is received with a maximum delay of ΔT_{max}. It is a narrowband signal if:

$$\Delta T_{max} B_s \ll 1 \tag{4}$$

For narrowband signal complex envelop becomes:

$$\tilde{s}(t - \tau_n) \approx \tilde{s}(t), \quad n = 0, \ldots\ldots\ldots, L-1 \tag{5}$$

This approximation modifies s(t, p) into:

$$s(t, p_n) = \sqrt{2}\mathrm{Re}\{\tilde{s}(t, p_n)e^{j\omega_c t}e^{-j\omega_c\tau_n}\}, n = 0, ., L-1 \tag{6}$$

From (6), it can be said that a phase shift of $e^{-j\omega_c\tau_n}$can replace a delay line associated with delay $\hat{o}_{n.}$ For uniform array, a phase shift can be used to steer the main response axis (MRA) at any desired value. MRA is the direction of maximum absolute signal value. This leads to a situation where each antenna element has a complex weight w_n which controls the MRA and beam pattern characteristics of the array. w_n can be obtained as:

$$w_n = \frac{1}{L} e^{j\overline{k^T(\theta_{MRA}\varphi_{MRA})}} * \overline{p_n} \tag{7}$$

Where k is wavenumber and p is position vector.

For linear array, position vector have only one component, reducing the calculation of weight coefficient for each channel n into:

$$w_n = \frac{1}{L} e^{j(\frac{2\pi}{\lambda})p_z} \cos(\theta_{MRA}) \tag{8}$$

B. Signal Energy Maximization

This section deals with a beamforming algorithm to maximize the signal power at the receiver so that the energy could be harvested by the energy receiver. Let s denote the transmitted symbol, a^H and b^H denote frequency-flat 1 X L complex channel vector from transmitter to information receiver and energy receiver respectively. The received signal at information and energy receiver are given respectively by:

$$y_{inf} = a^H w_2 s + z_{inf} \tag{9}$$

$$y_{egy} = b^H w_2 s + z_{egy} \tag{10}$$

Where w_2 is the L X 1 beamforming vector applied to the transmitter, and z_{inf} and z_{egy} are additive white complex Gaussian noise with variance $ó^2/2$.

It is not necessary for the energy receiver to convert the received RF band signal to baseband signal in order to harvest the energy contained in the signal. From the law of conservation of energy, the harvested power can be given by:

$$P_T = \eta | b^H w_2 |^2 \tag{11}$$

Where P_T is total harvested RF band power and ç is the conversion efficiency of the energy harvester circuit. ç account for the losses incurred by the circuit while converting RF energy to electrical energy.

Mathematically, our objective problem for maximizing harvested energy can be represented by:

$$P_1: \quad \max_{w_2} |b^H w_2| \tag{12}$$

$$subject\ to \quad \sqrt{\sigma^2(2^r - 1)} - |a^H w_2| \le 0 \tag{13}$$

$$\|w_2\| - \sqrt{p} \le 0 \tag{14}$$

Where r is the rate target for information receiver and P is the maximum power limit of the transmitter. A similar type of problem has been discussed in [9] in which the objective is to maximize the information rate at the information receiver subject to the condition that the power at the energy receiver is below a threshold.

The above discussion holds well when Channel State Information (CSI) of the receiver is perfectly known to the receiver. But when CSI is not perfectly known i.e. the esti

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mated CSI is slightly different than the exact value, channel can be modeled as:

$$a = \hat{a} + \Delta a \quad (15)$$

$$b = \hat{b} + \Delta b \quad (16)$$

In this paper, we assume that the channel has zero estimation error i.e. Äa and Äb are zero. Therefore, solution to the above problem P1 gives the weight vector w_2 which maximizes the power of the signal at the receiver.

III. Hybrid System

In section II, we have obtained the weight vector w_1 (of the order of L X 1) for steering the signal in the desired direction and weight vector w_2 to maximize the power of the signal at the energy receiver.

A hybrid system is proposed that can not only steer the signal in desired direction but also can maximize the signal power at the energy receiver. At transmitter, the signal is multiplied by a weighting factor that changes the amplitude and phase of the signal. When this signal is incident on an antenna, the signal has increased amplitude, resulting in increased power at the receiver. The weight vector w for this hybrid system can be obtained by the following mathematical equation:

$$w = w_1 * w_2 \quad (17)$$

The weight w has both amplitude and phase i.e. is a complex entity. Amplitude part of w is used to increase the signal strength at output of the Digital to Analog Converter (DAC) at the transmitter and the phase is used to steer the signal. Weight vector w incorporates both the steering vector and power maximization. The combined system thus steer the signal and have maximum power at the receiver so that the signal energy, when harvested could provide high power to charge the device.

A. Digital Beamforming Transmitter Design

Digital Beamforming plays an important role in the field of wireless communication. It provides all the benefits of digital domain. Bulky and costly phase shifters and amplifiers used in Analog Domain are replaced by simple multiplication in Digital Domain, which can be performed by a simple computer.

A simple architecture of a Digital beamforming transmitter is shown in Fig. 2. Here we have taken four element antenna array at the transmitter for the purpose of simplification. The DBF transmitter has three main stages: the CWM stage, the Digital-Up Converter (DUC) stage, and the RF Modulation Stage. The RF Modulation is not part of the Digital Beamformer, but it is important in the implementation of the Phased Array Antenna (PAA).

The first stage in the DBF transmitter is the Complex Weight Multiplier (CWM) stage. It controls the amplitude of the in-phase and quadrature signals prior to the Digital-Up Conversion. The CWM stage receives the information signal as input, multiplies the signal by the real part and imaginary part of the complex weight assign to the channel, and outputs an in-phase signal and a quadrature signal[10].

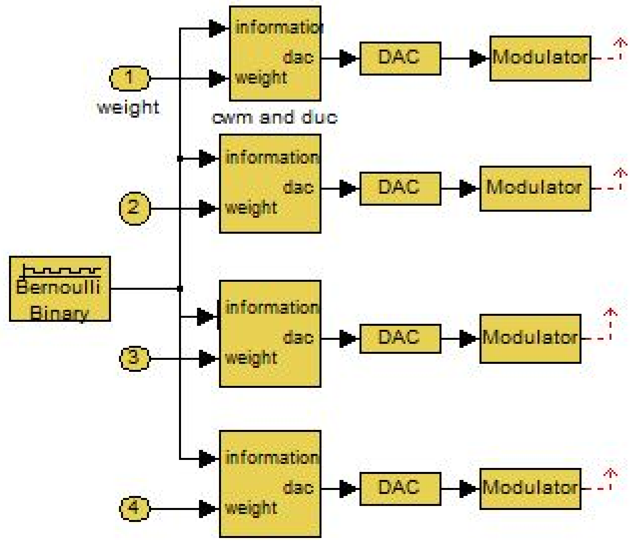

Figure 2. Block diagram of a DBF transmitter

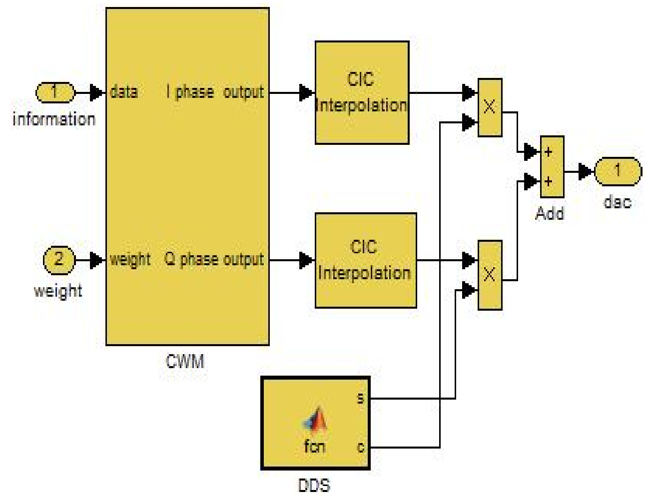

Figure 3. Diagram of CWM and DUC

In Fig. 4. A block diagram of complex weight multiplier is shown.

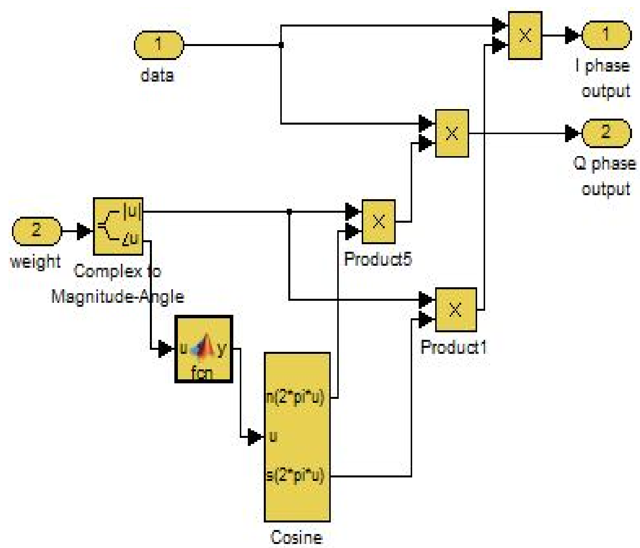

Figure 4. Complex weight multiplier

The second stage in the DBF transmitter is the Digital-Up

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Conversion (DUC) stage. The DUC receives two baseband signals (in-phase and quadrature signals) and modulates these signals into a single real bandpass signal. Fig. 3. Shows the inner diagram of a single "cwm and duc" block.

IV. Simulation Results

This section provides numerical results to verify the effectiveness of the proposed beamforming algorithm for power and information transmission. We considered four element antenna array at the transmitter i.e. (L = 4). We set the maximum power limit at the transmitter as 10 i.e. (P = 10). Channel from transmitter to the receiver is assumed to be Rayleigh fading channel with noise covariance $\sigma^2=1$. The channel vector is normalized as $||a||^2 = ||b||^2 = 4$ and rate target is fixed at r = 5.

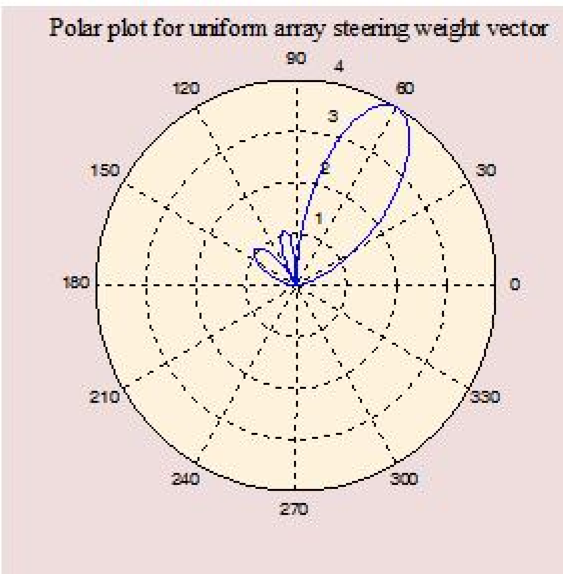

Figure 5. Polar Plot of Beam pattern magnitude of DBF using uniform weights and pointing at $\theta_{MRA} = 60^o$

A polar plot of Beampattern magnitude for the problem stated in section II. A. is presented in Fig. 5. Polar plot displays the distribution of signal amplitude over azimuth plane. MRA (Main Response Axis) is the angle of maximum magnitude from the transmitter in the azimuth plane. Maximum signal amplitude obtained at $\theta_{MRA} = 60^0$ is 4, while the maximum side lobe magnitude is 1.0811. Thus maximum mainlobe to sidelobe magnitude ratio is calculated to be 3.7. Maximum mainlobe to sidelobe signal magnitude ratio is the measure of how effectively the signal power is concentrated in the desired direction (mainlobe) than in other direction (sidelobes). Total energy of the system at output of transmitter, for one thousand samples of the information signal is calculated to be 3.12 KJ.

For the problem stated in section II.B., a polar plot of Beampattern magnitude is shown in Fig. 6. The MRA of the Beampattern is pointing at an angle of 90^0. This is due to the fact that the weights used for this problem have zero phase components. It only increases the strength of the signal.

In Fig. 7, we plotted a polar plot of Beampattern magnitude at $\theta_{MRA} = 60^0$ for the proposed algorithm described in section III. . Maximum signal magnitude obtained at $\theta_{MRA} = 60^0$ is 17.0142, while the maximum side lobe magnitude is 4.0242. Thus maximum mainlobe to sidelobe amplitude ratio is calculated to be 4.23. Total energy of the system at output of transmitter, for one thousand samples of the information signal is calculated to be 58.8 KJ.

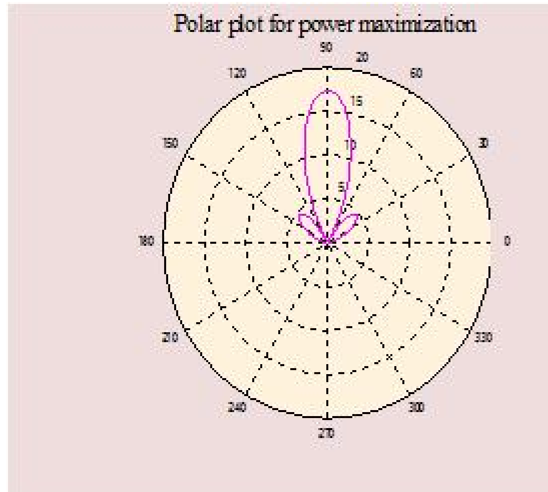

Figure 6. Polar plot of Beampattern magnitude of a 4-element linear DBF for power maximization

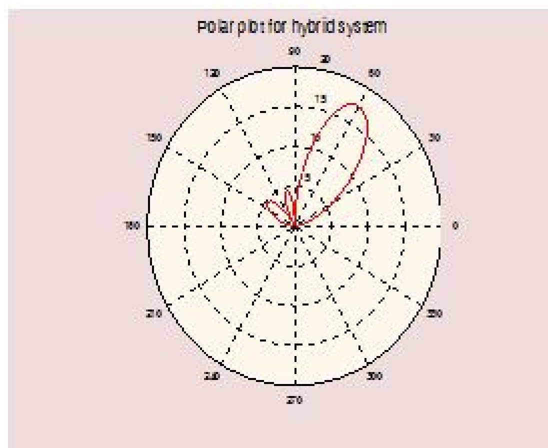

Figure 7. Polar plot of Beampattern magnitude of DBF using proposed algorithm and pointing at $\theta_{MRA} = 60^o$

Fig. 8. Displays the rectangular plot of the Beampattern magnitude (in dB) verses angle of arrival (in degrees). It can be seen from the figure that the magnitude of the proposed algorithm is about 50 dB higher than that using uniform weight.

Simulation results shows that maximum mainlobe to sidelobe magnitude ratio for the proposed algorithm is about 15% higher than that using uniform weight for signal steering. The total energy of the system at output of the transmitter, for one thousand samples of the information signal in case or proposed algorithm is roughly 4.8 times that of the system using uniform weight.

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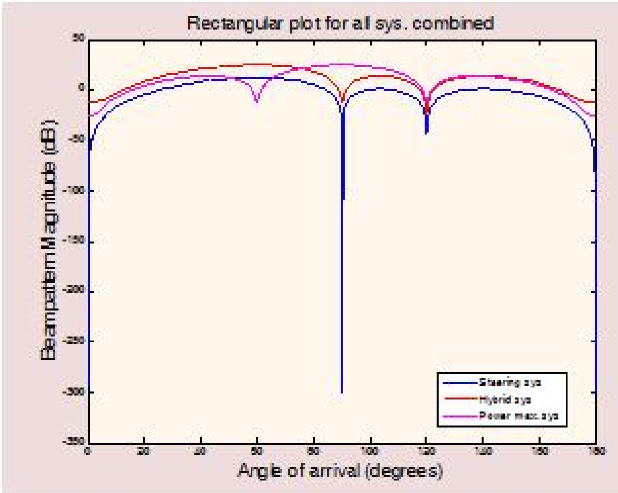

Figure 8. Rectangular plot of Beampattern magnitude for system described in sections II and III

Conclusions

This paper investigates the design of wireless communication system for simultaneous power and information transmission using Digital Beamforming. A beamforming algorithm is proposed that maximizes the transmit signal power, maintaining a minimum information rate as well as steer the signal in the desired direction. The performance of the proposed algorithm has been demonstrated by simulation. The proposed algorithm can be extended for systems with imperfect knowledge of CSI. The future work may include the use of the proposed algorithm for MIMO systems which will increase power and information rate of the system.

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